APPROACHES TO MODELLING LONG-TERM LANDSCAPE EVOLUTION: LESSONS FROM ICE SHEET MODELLING

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ABSTRACT

Advances in the understanding of physical principles underlying geophysical processes have enabled us to develop complex numerical models of landscape evolution. These advances have shaped recent contributions to the long-running debates within geomorphology concerning the relative value of approaches which emphasize the unchanging (immanent) physical principles underlying geomorphic processes, compared with the historical (configurational) nature of landscapes which rely on circumstantial conditions for their existence.

This paper uses examples from glaciology to assess the extent to which the developments in short-term process studies and numerical models assist us in understanding the long-term processes of landscape evolution. The implication is that while both developments stress the immanent nature of geophysics, their limitations highlight the need for a balanced approach incorporating both immanent and configurational approaches. The key is that it is possible to explain and understand long-term processes without necessarily being able to predict them with numerical models. Modelling approaches should stress the contexual nature of the studies by means of a full exploration of possible outcomes of different model components. © 1997 by John Wiley & Sons, Ltd.

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INTRODUCTION

The aim of this paper is to examine the extent to which modelling advances provide a base from which we can understand long-term landscape evolution, by showing how similar problems have been tackled within glaciology. The analogy is apt because both long-term landscape evolution and one focus of glaciology – the study of ice sheet evolution – deal principally with the vertical movement of a surface over long time-scales.

The relative merits of ‘immanent’ (timeless) and ‘configurational’ (timebound) approaches to geomorphological explanation have been the focus of long-running debates within geomorphology (Strahler, 1952; Simpson, 1963; Schumm, 1991; Frodeman, 1995). The former reflects the existence of inherent physical processes and principles which may be described by mathematical regularities or ‘laws’. The latter reflects the historical nature of landscapes, which develop because of the conjunction of particular conditions through time (Kennedy, 1992).

In the past 20 years, three developments have had considerable impact on the themes underlying these debates. The first is the preponderance of short-term process studies. These have undoubtedly led to a deeper understanding of the physical mechanisms which drive geomorphic processes. The second has been the continued, and rapid, development of numerical modelling, aided by increased computational power. This permits the computation of more complex numerical models on model time-scales which are of interest to geomorphologists studying landscape evolution. The final development is the blurring of the boundaries between geophysical disciplines, which engenders new and necessary knowledge, tools and techniques to tackle long-term, large-scale geomorphological problems. The result has been the development of techniques

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relevant to the long time-scales involved (e.g. Brown *et al*., 1994) and landscape models which incorporate both surface processes and crustal dynamics. This latter development has been considered at length elsewhere (Merritts and Ellis, 1994) and will not be considered in this paper.

SHORT-TERM PROCESS STUDIES

Short-term process studies are the tools by which we can obtain an understanding of the basic physical principles of mechanics and fluid mechanics which manifest themselves in geophysical processes such as weathering, erosion, transportation and deposition (Strahler, 1952). In the terminology of Simpson (1963), the studies examine the immanent physical processes and principles in geophysics.

The principal use of this understanding in long-term studies is to quantify physical relationships between variables, which can then be used in experiments with numerical models. This understanding is used in a range of ways. At one end of the spectrum, it provides parameterizations for relationships whose physical basis is poorly known. At the other end of the spectrum, it is used to derive some mean or range of values for relationships for which the physical basis is known in detail. Unless data are available to the contrary, these parameterizations must be assumed to be spatially and temporally invariant for the modelled time period. This may be physically reasonable. However, in long-term studies, the data required to confirm the nature and applicability of such assumptions are rarely accessible. For example, the nature of a glacier's hydrological system is known to change both through an annual cycle and on longer time-scales, and it substantially affects glacial flow. Any model which seeks to model glacial flow over long periods must parameterize such variations on the basis of short time-series data, which may be hopelessly biased to one type of hydrology. Thus the model of the system with these parameterizations is unlikely to be representative of the long-term changes in hydrology, and hence glacial flow.

Furthermore, it is not clear that correct parameterizations of short-term processes necessarily lead to an understanding of longer period processes in non-linear systems. This can best be explained by considering the response time of a system, which is the time taken to return to an equilibrium after perturbation. By necessity, processes with short response times are assumed to be in a quasi-equilibrium with processes which have longer response times. For example, ice sheets have response times of thousands of years, while the atmosphere has a response time measurable in days and, in the context of modelling the evolving system, is assumed to be in equilibrium with the ice surface. However, in reality, there are long-term mass and energy fluxes which occur as a result of a small disequilibrium between these processes with different response times. The difficulty of measuring or modelling these fluxes is that they can be orders of magnitude smaller than the processes themselves, and hence are often below the resolution of accessible data. Saltzmann (1985) argues that the existence of these fluxes, coupled to the non-linear nature of environmental systems, means it is unlikely that a detailed understanding of components with short response times will ever provide a measure of fluxes or processes involved with long-term environmental change. This sets fundamental limits to our knowledge of the evolution of the whole environmental system.

NUMERICAL MODELS

Numerical models are useful in the environmental sciences because of the time and space constraints of experiments conducted on, and observations of, environmental systems. Models can be used to accelerate/decelerate time and explore the state of a system on time-scales not amenable to human observation. At the heart of numerical models are quantified relationships between variables, and these are presumed to represent the physical relationships within an environmental system. To best explain the nature of models, I will analyse the procedures involved in the development of ice sheet models. This will clarify the assumptions implicit in their design, which carry profound implications for modelling other long-term processes such as landscape evolution.

Obtaining quantified relationships between variables involves three stages: choosing the appropriate variables, quantifying relationships between variables, and calibrating these relationships. The choice of appropriate variables is a subjective assessment as to what is important within the spatial and temporal scales of

interest. The large spatial scales and long time-scales inherent in models of ice sheets or landscape evolution yield additional complications, since many boundary conditions cannot be treated as spatially or temporally homogeneous over the model domain. This substantially increases the difficulties of modelling such systems.

Quantifying relationships between variables follows two courses, both reflecting the need for short-term process studies. Firstly, the physical processes may be understood to some arbitrary level of detail. Since excessive detail is unhelpful, these relationships can be quantified with some mean value at the appropriate scale, perhaps with a superimposed stochastic component. For example, the use of a cubic power in the Glen flow law for ice is a gross simplication of the strain on ice resulting from an applied stress (Glen, 1955; Nye, 1957):

$$\dot{\varepsilon}_{xy} = A\tau^{n}_{xy}$$

where $\dot{\varepsilon}_{xy}$ is the shear strain rate, τ_{xy} is the shear stress, the value of A varies with temperature according to the Arrhenius relation, and n is a constant generally taken to be 3. The actual strain will depend on factors such as the temperature of ice, the orientation of grains, and impurities within the ice. This parameter is thus a useful generalization of the complex processes involved with ice flow. It was derived at a laboratory scale and is not necessarily applicable to all flow phenomena at all scales.

Alternatively, the knowledge of the underlying physical process may be poorly known, in which case a purely empirical relationship is developed between variables. Although this approach is not particularly elegant mathematically, it provides the only feasible approach to exploring many physical problems, and could be more widely applied. For example, the physical basis for glacial erosion remains elusive. However, it is possible to quantify erosion by use of a bulk erosion 'law', which relates the erosive power of the glacier to, for example, the basal shear stress, and which has been calibrated against existing glaciers. Since the relationship is not causal it must be assumed that the conditions which led to the original observations are invariant spatially and temporally.

Finally, the calibration of relationships between variables proceeds from the need to minimize errors between the modelled and actual system. These errors arise from the need to simplify processes and to average variables spatially and temporally, such that a model can only represent the actual system approximately. For example, measured values for the temperature-dependent parameter, A, in the Glen flow law vary markedly, but can be categorized according to temperature ranges. The best solution appears to be to adjust model parameter values within their range of uncertainty to represent the system more accurately. Once these values have been set, it must be assumed that these conditions (or characterizations) do not change.

At this point the most appropriate numerical method for solving the relevant equations must be applied. Perhaps the most common approach is to use finite difference numerical models, which subdivide the model domain into equally spaced nodes. At each node and at specified model-time intervals, the relevant equations are solved to calculate an approximation to the exact instantaneous value of the variables. This process of averaging introduces small numerical errors which propagate through the model simulation, and fundamentally limits the extent to which the model represents the fluxes of mass and energy occurring in the real system. Furthermore, all processes operating below the spatial scale of the model nodes must either be incorporated stochastically, in the form of an empirical parameterization, or ignored.

Predictions of the model are then tested against independent data. This 'validation' is useful confirmatory evidence that the model can reproduce empirical data. However, it cannot demonstrate that the model is an accurate representation of the system under any condition. It only indicates that the model prediction matches empirical observation under the tightly specified conditions of the test data. It is trivial to note that only in the closed systems of mathematics or logic can proof, in an absolute sense, be demonstrated. In the open conditions of environmental systems conditions can never be exactly reproduced, and models can never be formally verified. Instead, the onus is on the modeller to establish a sufficient degree of confidence in the model. For a more detailed discussion of verification and validation of numerical models, see Oreskes *et al*. (1994).

The implications of model development for long-term landscape evolution are profound. While improved model parameterizations reflect the advances in understanding of geophysical systems, the models are, by necessity, substantial simplifications of the immanent geophysical processes applicable to one range of temporal and spatial scales. Regardless of the scale in which we are interested, no model can incorporate all processes at all scales. Detailed simulation of landscape evolution is not, in general, possible because of the

inherent loss of information at scales below the averaging (grid) scale of models, and because the necessary data to parameterize all relationships within the model are unavailable. Thus, ‘prediction’ of the system from an unknown initial condition to the present provides a false illusion of rigour in understanding the nature of the system.

However, this does not mean that we cannot understand or explain how a particular landscape evolved. At this point, either we might argue that more data are needed to attain predictive power, or we might accept that there exists an asymmetry between explanation and prediction (Scriven, 1959; Simpson, 1963). The remainder of the article is based on the latter premise.

MODELLING AS A HISTORICAL SCIENCE

This brief assessment of short-term process studies and numerical modelling leads me to conclude that the recent focus on, and successful utilization of, immanent physical principles in geomorphology has led to our present situation, which accentuates the need for configurational approaches to assist with explanation and understanding of landscape evolution. The key problem associated with the use of models rests on the utilization of modelling as a predictive tool. The belief that model prediction necessarily provides a more rigorous understanding of the system is false. Rather, the understanding derives from the better contextual knowledge of the system, and this is dependent on using models as heuristic devices to explore possible outcomes of different components of the system. This is most easily achieved by evaluating all reasonable values of different model parameters by means of sensitivity studies.

A more appropriate methodological approach is to acknowledge the interpretative and historical nature of modelling, as this provides a more coherent account of how we come to understand a complex open system. The essence of the historical approach is the different criteria for what counts as explanation (Frodeman, 1995). While it is possible to identify general laws, we are actually interested in particular events at specific locations which produce unique landscapes. This is summarized by Hindmarsh (1990), with reference to ice sheet models, as follows: ‘Large scale models are founded on very general statements (conservation laws etc.) and then used to make very specific statements about what happens under a particular set of circumstances. One is asserting that a large number of things are important while hoping that the results reveal the simplicity we see around us.’

The interpretative nature of modelling can be exemplified by the loose criteria for what is defined as a ‘good fit’ between model output and reality. Often, reasons are given for why the model does not exactly reproduce observed field data, and these reasons then count towards explanation of the system. Thus, a bad fit can provide as much explanation as a good fit, or arguably more, since when there is a good fit it is not clear whether it is because the physical processes are correctly modelled or because there is some fortunate conjunction of model output with observed data (Oreskes *et al*., 1994).

Explanation of a system actually derives from other forms of reasoning such as the use of analogies; for example, a present-day environment may be taken to be analogous to a past environment. However, this type of reasoning can never be a substitute for data of past environments, since a full set of analogues of past processes and landforms does not exist today. The implication for geomorphological explanation is that the results of short-term process studies cannot be used to explain landscape evolution; instead, they should be taken as benchmarks of modern-day processes. This latter approach stresses the immanent nature of geomorphic processes, whilst making no claims concerning the availability of all the necessary information required to derive the configurational elements of a landscape. They provide a context in which we can place landscape evolution; it is from this context that we can utilize other forms of evidence to obtain an explanation consistent with available data. The reasoning and explanation become dependent on the overall coherence of the theory, rather than being derived through the use of a predictive landscape model, and provide us with our understanding of the system.

WIDER IMPLICATIONS

The predominance of short-term process studies and the advances in computational power have resulted in

geomorphological approaches which stress the immanent, or timelessness, over the configurational or historical. However, faced with problems of long-term processes, it becomes apparent that both approaches are required to attain an understanding of the geophysical system. The use of models, developed with the best parameterizations of physical processes, will not ‘explain’ the operation of a system by the attempt to predict its evolution. There exists an asymmetry between the possibility of prediction and the existence of explanation.

Treating the modelling within an interpretative and historical context is a more accurate description of the modelling approach, though one that is rarely acknowledged explicitly. It provides a better understanding of both strengths and limitations of modelling. The interpretative approach can be summarized by the need for context: our understanding of model output depends on a broader understanding of the problem we face, and our broader understanding stems from our perception of the problem. Since the landscape we are examining is unique, our preconception depends on the existence of related structures or concepts, and their prevailing interpretations.

The historical approach can be summarized by noting that our interest lies not in obtaining general laws, but in the conditional events which create a landscape. When modelling geological timespans, the implication is that short-term process studies, which are used to quantify parameterizations within models, are useful as benchmarks. They should be incorporated into models without making substantive claims to the predictive power of models as a means of explanation.

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